SOME ASPECTS OF THE CONTROL AND STABILIZATION OF THE RF ACCELERATING VOLTAGE IN THE TRIUMF CYCLOTRON

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ABSTRACT

This paper discusses the system developed to control the 2 MW 23 MHz RF system at TRIUMF. Included are means of pulsing through the multipactoring region; RF accelerating voltage amplitude and phase control; provision of self-excited and driven modes of operation; fine tuning of the resonators; phase and amplitude control of third harmonic voltage for flat-topping of the RF waveform. Results obtained with a prototype control system on the central region cyclotron are included.

The prime objective of the RF control system is to ensure an accelerating voltage of stable amplitude and phase, with the correct proportion and phase of third harmonic for waveform modification.

Problems encountered in achieving these ends are multipactoring, resonator detuning, amplitude modulation noise, phase modulation noise, and beam loading.

The beam load in the TRIUMF cyclotron is a small fraction of the total resonator load at the design 100 μA current level and would only be equal to this load at a beam current of 2 mA. System instabilities caused by reactive beam loads are therefore small at the fundamental frequency of 23.1 MHz. Since the third harmonic power levels are only a few per cent of the fundamental power, the beam power can have significant effects on these power requirements. At beam currents of 100 μA power will be coupled into this resonator mode through the beam, and it is anticipated that third harmonic power should be removed from the system. A resistive load capable of abstracting third harmonic power will be inserted into the third harmonic transmission line at high beam currents to help to stabilize the system.

The system at present developed to a satisfactory level for the central region cyclotron is represented in the block diagram, Fig. 4. The control functions are directly applicable to the main TRIUMF cyclotron. A reasonable degree of automatic functioning is incorporated so that remote operation from the main cyclotron control desk is achieved by means of a minimum number of control and monitoring points.

The required RF amplitude and phase tolerances are several orders of magnitude smaller than those attainable by an unregulated RF system. It is desired to have the level of amplitude modulation reduced to less than -94 dB. Because feedback regulation reduces a system's output error by an amount approximately equal to the gain of its feedback loop, feedback regulation will be used to maintain the required RF amplitude and phase tolerances in the TRIUMF cyclotron. The amount of regulation possible is not, however, unlimited since the gain of the feedback loop must be less than unity when the phase shift around the loop is 180 deg. If the gain is larger, the feedback system will oscillate.

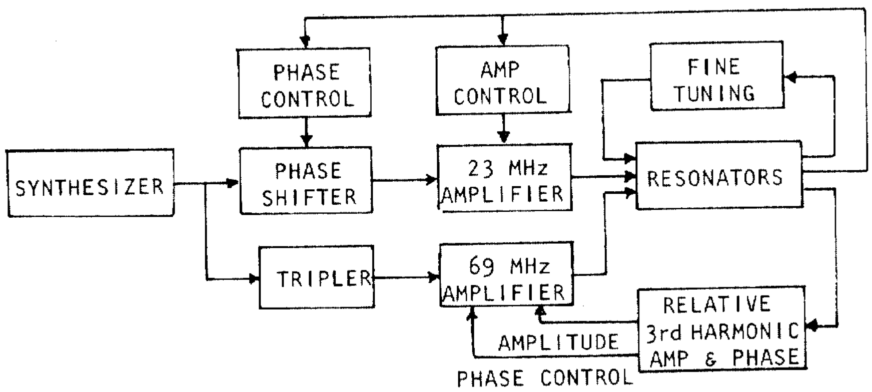

Fig. 1. TRIUMF RF feedback control loops

Fig. 1 indicates the major feedback loops in the TRIUMF RF control system. These regulate the amplitude and phase of the fundamental and third harmonic and also provide fine tuning for the resonators. Note that the actual amplitude and phase of the fundamental are controlled, while for the third harmonic it is the amplitude and phase relative to the first harmonic that are controlled.

As a first step in the design of the required systems the input-output relationships were found for the elements comprising the feedback loops. For small modulating signals the amplifier chains (both first and third harmonic) have transfer functions of the form

$$T(S) = \frac{K}{1 + (2Q/\omega_0)S} \quad (1)$$

where Q = amplifier Q,
ω_0 = operating frequency.

For amplitude modulation K = voltage gain, for phase modulation $K \equiv 1$. The output from each amplifier chain is fed to a block composed of the appropriate transmission line coupled to the resonators. As a first-order approximation the transfer function given by Eq.(1) could be used, letting Q be the appropriate resonator Q. A more accurate transfer function was derived using the equivalent circuit of Fig. 2.

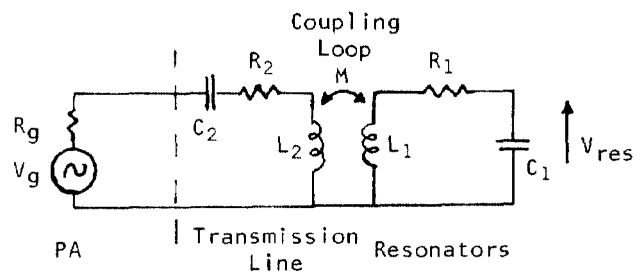

Fig. 2. Equivalent circuit used to derive the transmission line-resonator transfer functions (for small signal amplitude and phase modulation)

For small signals this equivalent circuit gave an amplitude modulation transfer function

$$T(S) = \frac{K_R(1 + S/\alpha_2)}{(1 + S/\alpha_0)(1 + S/\alpha_1)} \tag{2}$$

where K_R = voltage gain.

For phase modulation the same function results except that $K_R \equiv 1$. For the CRM cyclotron it was found (and experimentally verified) that

$$\alpha_0 = 2 \times 10^4 \text{ sec}^{-1}$$
$$\alpha_1 = 5.2 \times 10^5 \text{ sec}^{-1}$$
$$\alpha_2 = 7 \times 10^6 \text{ sec}^{-1}$$

Calculations also indicate that for the small, low-frequency (with respect to the frequency of the RF) modulating signals expected there will be no significant interaction between the phase and amplitude control systems.

The fine tuning system indicated in Fig. 1 is necessitated by the high Q of the TRIUMF resonators. Considering the resonators as a single tuned circuit yields

$$|\Delta\theta| \simeq 2Q_R\left(\frac{\Delta\omega_R}{\omega_R}\right) \qquad \text{(phase change)}$$

$$|\Delta A| \simeq 2A_R\, Q_R^2\left(\frac{\Delta\omega_R}{\omega_R}\right)^2 \qquad \text{(amplitude change)}$$

where

Q_R = resonator Q (≥6000)

A_R = amplitude for driving frequency = resonant frequency

$\left(\frac{\Delta\omega_R}{\omega_R}\right)$ = fractional change in resonant frequency.

($\Delta\omega_R$) must therefore be kept small so that the required correction in amplitude and phase is within the range of the feedback systems. The organization of the fine tuning system is shown in Fig. 3; since the actuation of the tuning diaphragms is accomplished pneumatically, this system will be able to correct for only slow changes in resonant frequency. Calculations and measurements indicate that the maximum rate of correction will be of the order of 1 Hz.

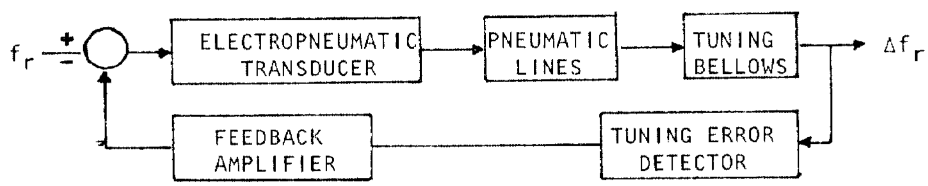

Fig. 3. TRIUMF resonator fine tuning system

The block diagram, Fig. 4, shows seven main feedback loops, not all of which are in operation simultaneously. A logic unit handles operator commands, activates the appropriate feedback loops, and pulse modulates the RF amplifier drive.

In order to break through the multipactoring region when RF power is applied to the resonator, the tip voltage must rise rapidly (≈1000 V/μsec). Calculations show that this condition is met with the TRIUMF RF system, provided that the driving frequency is accurately tuned to the natural frequency of the resonator system, and that the input power is sufficient to give a steady-state voltage of >100 kV. Initial drive, therefore, is at full power. If multipactoring does not occur, the logic unit senses the rise in resonator voltage and activates the feedback amplifier in the amplitude control loop. The resonator voltage is then stabilized at a level corresponding to a reference voltage, or resonator voltage set-point. However, if multipactoring occurs when RF power is turned on, the resonator voltage is clamped at a few hundred volts, and the RF power amplifier sees a serious mismatch. After 1 msec the logic unit pulses off the drive and waits 25 msec before pulsing on again. Thus the system is driven with high power pulses with a 1:25 duty factor until multipactoring punch-through is achieved.

After cw operation has been established, should the RF voltage fail through any cause, most likely due to arc-over in the resonator, the

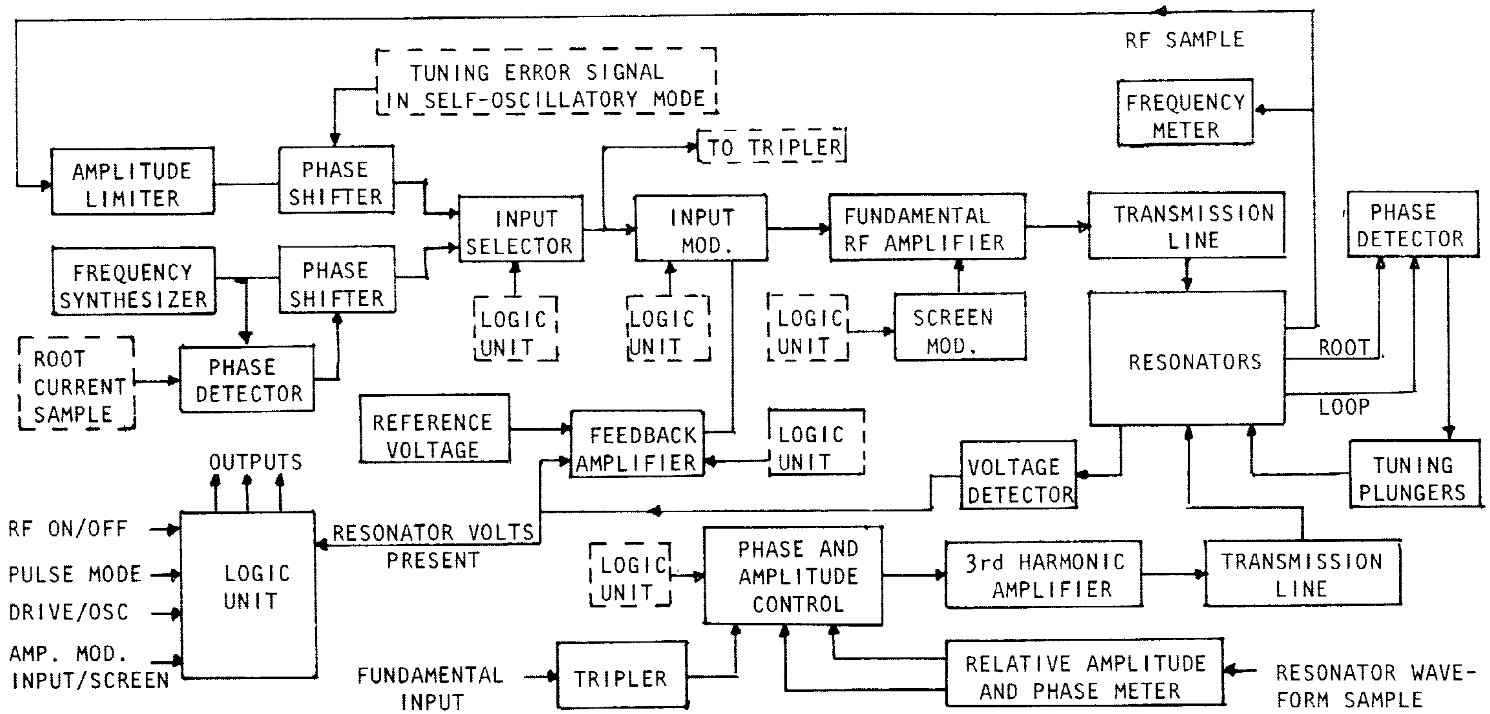

Fig. 4. TRIUMF RF control system

RF drive is pulsed off for 25 msec as above. A counter, set for 1, 2, 4 or 8 counts, shuts off the drive permanently if the preset fault count is reached with less than 1 sec between successive faults.

The operating frequency of the system is determined primarily by the resonator, with its Q of 5000 giving a bandwidth of 2 kHz. The resonant frequency, nominally 23.1 MHz, varies through mechanical distortions of the panels due to cooling water pressure variations and temperature changes. The largest frequency drifts are caused by temperature transients when the RF power level is changed. This effect makes it virtually impossible to drive the cold resonators from a fixed or manually-tuned frequency source. A frequency change of 20 kHz is experienced during the first few minutes of operation. The problem is solved by operating the system in the self-oscillatory mode. A signal from the resonator is fed in the correct phase to the RF amplifier input, and the resulting oscillatory frequency is determined by the resonator. A phase shifter in the signal path is controlled by a tuning error signal derived from the resonator and maintains zero phase shift around the oscillatory loop. Of course, the system is started up using frequency synthesizer drive and becomes self-oscillatory only when multipactoring has been dealt with. When the frequency stabilizes after the initial temperature transient, the system is switched back, by the operator, to synthesizer drive. Now the tuning error signal drives the fine tuning plungers in the resonators to handle small detuning effects. In this driven mode of operation a phase control loop, referenced to the synthesizer, reduces accelerating voltage phase modulation, mainly caused by fast mechanical vibration of the resonator.

Provision has been made to control RF power by modulating the power amplifier screen voltage as an alternative to modulating the RF drive. In the screen modulation mode the earlier stages of the RF amplifier are run in a near-saturation condition so that their noise contribution is greatly reduced. A disadvantage of this control mode is that its dynamic range is small, and it can therefore be brought into operation only when the resonator has stabilized at a particular power level.

Third harmonic power may be fed to the resonator at any time the fundamental frequency is operating cw. The amplitude of the third harmonic component of the resonator voltage and the phase relationship of the two frequency components are controlled by two feedback loops. Two separate modes of cyclotron operation are possible. The accelerating voltage is defined by the expression

$$v = V_0\left(\cos\omega t - \varepsilon\cos(3\omega t + \delta)\right).$$

For large duty cycle operation of the cyclotron, ε is set in the range 0.2 to 0.3 and held stable to ±0.005, while $\delta \simeq -25$ deg and held constant to ±1.5 deg.

When a high energy resolution beam is required, the values of ε and δ become 0.1200 ± 0.0001 and 0 deg ± 0.15 deg. Circuitry for measuring the values of ε and δ in the RF waveform have been described;[1] the recovered parameters are then used by the feedback loops to stabilize the waveform.

At the main cyclotron control desk the control functions provided are simply RF on/off, third harmonic on/off, driven/self-oscillatory operation, frequency synthesizer tuning, resonator voltage set-point, and third harmonic phase and amplitude control.

Except for the third harmonic functions and resonator fine tuning, the system has been fully tested with the central region cyclotron at full power, and with a beam.

REFERENCES

1. R.H.M. Gummer, IEEE Trans. Nucl. Sci. NS-18, 371 (1971)

DISCUSSION

SCHATZ: Could you comment on how you expect to stabilize the voltage to 10^{-5}?

ERDMAN: We have DC filaments in the amplifiers themselves. We will be running the driver amplifiers in the saturated mode. So far as the system is concerned, we will be doing the amplitude control through the screen circuitry. As for the amplitude noise level, we have gone to low noise circuitry. The system is supposed to have a -80 dB noise level as it starts. We need about 94 dB to give us the stability level, and we expect to get that additional 14 dB through feedback in the system.

SCHATZ: How do you expect to measure the amplitude in the resonators to that accuracy?

ERDMAN: We will measure the amplitude in the resonator capacitor pick-up probes, by means of which we will expect to get 1 part in 10^4 in the system. We have worked out the positions of these probes; they are temperature-compensated probes put in such position that any temperature fluctuation effects do not affect the signal sizes, and the capacitors are temperature compensated. The final factor of 10 in stability will come through pick-up sensors on the beam itself through the analysing system to give us that extra factor of 10, to give us 10^5.